MULTI-PARAMETER ANALYSIS IN EDDY CURRENT INSPECTION OF AIRCRAFT ENGINE COMPONENTS

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INTRODUCTION

One of the major problems limiting the life of critical aircraft engine components, such as compressor discs and spacers, is the formation of low cycle fatigue (LCF) cracks in the fastener bolt holes. Such cracks are often initiated from corners and their surfaces are oxidized during the engine operation. Eddy current techniques using rotating probes are considered to be the most appropriate for detecting bolt hole cracks. Inspection according to damage tolerance criteria requires repeatable detection (90% probability of detection with 95% confidence) of cracks of the order of 0.125 mm (0.005"). If only threshold setting methods are used by a human analyst or implemented by means of electronic instrumentation, detectability can be low since it is difficult to distinguish between the actual flaw signal and noise in the eddy current signal as both are of similar amplitude. However, in certain cases, searching for structure in the noisy waveform can provide indications of defects that escape detection by threshold setting techniques. One way of achieving this is by using multi-parameter signal analysis and pattern recognition methods.

In pattern recognition, the whole signal is digitized, several parameters (features) are extracted and compared with those of known patterns that have been stored. The objective is to classify unknown patterns into known classes on the basis of the similarity between their features.

A system has been developed which uses a standard eddy current instrument, an automated XYZ table and a commercial pattern recognition software package. The system has been used to inspect fastener bolt holes of an aircraft engine compressor disc with service-induced LCF cracks. In this paper, the effectiveness of pattern recognition in recognizing cracks has been compared with the conventional visual analysis of the eddy current impedance plan signals by an experienced operator as well as threshold setting on

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amplitude and phase signals. The results have been verified by pry opening all bolt holes and examining the fracture surfaces under a scanning electron microscope.

INSPECTION SYSTEM

The inspection system consists of a standard eddy current instrument equipped with a spinning probe (Elotest B1 SD), an automated XYZ table (Techno), a commercial pattern recognition software package (ICEPAK) and a computer (HP Vectra RS/20) for controlling the XYZ table and processing the EC signals. Eddy current signals are captured, digitized, displayed, processed and saved on hard disk for subsequent play back or printing. The system shows, in real-time, the digitized impedance plane representation (Figure 1-a) as well as the real (Figure 1-b) and imaginary (Figure 1-c) components of the EC signals along with the pattern recognition classification results. Alternatively, the overall inspection results can be displayed in graphic form and defective bolt holes identified using different colour codes. Further information on the inspection system can be found in Reference 1.

PATTERN RECOGNITION SOFTWARE

ICEPAK (Intelligent Classifier Engineering PAKage) is a commercial pattern recognition package developed by Tektrend International Inc. ICEPAK uses several steps to classify the signals. Data acquisition, transformation and extraction of features (parameters) are parts of the fact gathering process to present the data in optimal formats for processing by the computer. ICEPAK uses five procedures to classify signals and details of the algorithms used in each procedure are provided in Reference 2. The classifying procedures are; Linear Discriminant Function, K-Nearest Neighbour, Empirical Bayesian, Minimum Distance and Neural Network. The system is first trained on known signals and optimal features of the signal from different domains are automatically selected based on their discriminating ability. The optimal features are used with different classifiers and the recognition rates are evaluated. This exercise is iterated until the classifier performance is optimized. The classifier is then saved and recalled to classify unknown signals.

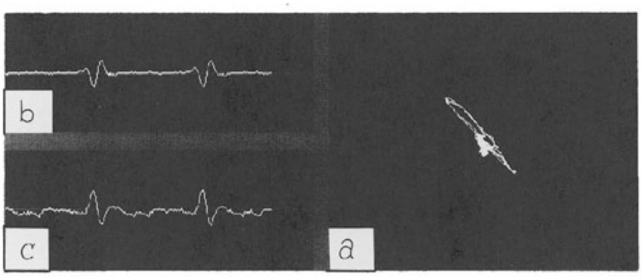

Figure 1. A computer display of digital eddy current signals from a bolt hole crack. (a) Impedance plane presentation, (b) Real (X) component and (c) Imaginary (Y) component.

EXPERIMENTAL PROCEDURES

An aircraft engine compressor disc, similar to that shown in Figure 2, was used to evaluate the performance of the system. The disc had been retired from service due to the development of low cycle fatigue cracks in the tie bolt holes. The disk material was AM-355, a precipitation hardened martensitic stainless steel and it was known, from experience, that cracks grow radially with the majority growing inwards toward the centre of the disc. There were forty 4.7 mm diameter bolt holes in the disc, thirty five of which were available for inspection since part of the disc had been already removed for other purposes.

A 4.4 mm diameter differential spinning probe with a frequency range of 50 kHz - 2.5 MHz was employed for inspections. The instrument frequency and gain were adjusted to 660 kHz and 42 dB respectively, settings which were found to be optimal for this inspection. The bolt holes were inspected automatically at six different depths and eddy current signals corresponding to each level were digitized and stored.

Three approaches were used for the analysis of the eddy current signals. First an experienced inspector was asked to analyze the impedance plan signals visually and to identify the cracked bolt holes. The inspector was then asked to set a threshold on the partitioned phase and amplitude signals to detect cracks. Finally, automated decision making using pattern recognition was employed.

For pattern recognition analysis, the system was first trained using known signals from cracked and crack free bolt holes obtained in previous disc inspections. Of the first four classifiers evaluated, the K-nearest neighbour procedure with three parameters produced an optimal recognition rate of 95% during training (the Neural Network classifier was not available at the time of this investigation). The optimal features were related to the signal amplitude and partial power in the power and auto-correlation domains. The optimal parameters and classifying procedure were stored and used to classify eddy current signals and to identify defective bolt holes.

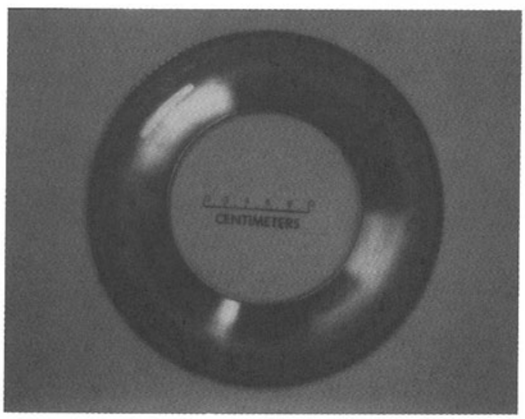

Figure 2. A photograph of the compressor disc used in the present investigation.

After inspection and classification, all bolt holes were pried open and examined using optical and scanning electron microscopy techniques to verify the presence of cracks and to determine the actual location and size of cracks. The pry opening procedure is schematically shown in Figure 3.

RESULTS AND DISCUSSIONS

The inspection results are summarized in Table I. The automated eddy current inspection with human interpretation of the impedance plane signals resulted in 13 detections, 19 misses and no false call. The largest crack missed was 0.6 mm deep. Partitioning of the signal into amplitude and phase components and analysis of both signals based on thresholding, increased the number of detections to 17 with no false calls. The largest crack missed in this case was also 0.6 mm deep. The higher detection level using the partitioned signals is attributed to the fact that for very small cracks there is a slight change in the phase angle that cannot be seen on the impedance plane signals which have a shape similar to the background noise. With the aid of pattern recognition, 28 cracks were detected, four cracks were missed which all were less than 0.15 mm in depth and there was one false call. In addition to the improved detection level, the use of pattern recognition also improved the total inspection and interpretation time as compared with the operator interpretation of the signals.

As seen in Figure 4, the service-induced low cycle fatigue cracks have smooth fracture surfaces which can be easily recognized under SEM from the rough fracture surfaces created during pry opening procedure. The cracks ranged from a few microns up to about 1 mm in depth and occurred in different shapes and locations. Most cracks initiated from the surface corners and propagated radially inward toward the bore of the disc. There were also some totally internal cracks as well as cracks initiating from the middle of the bolt hole, multiple cracks and outward propagating cracks.

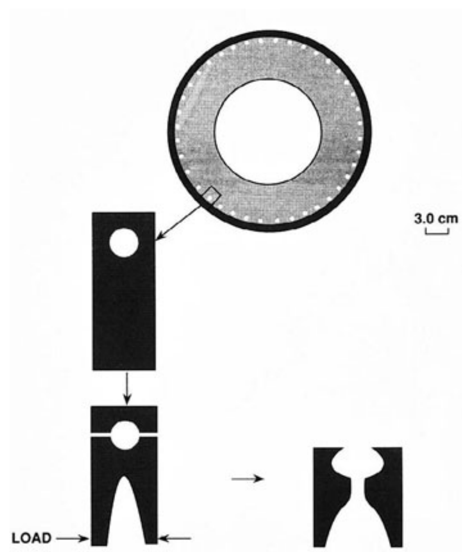

Figure 3. Pry opening procedure used for crack verification.

Table I

AUTOMATED EC INSPECTION DATA FOR A COMPRESSOR DISC

Hole No.	Operator Interpretation Using		Automated Interpret.	SEM
	Impedance Plane	Amplitude & Phase	Pattern Recognition	Crack Depth (mm)
1			d	0.05
2			d	0.01
3			d	0.06
4			d	no crack
5	d	d	d	0.55
6		d	d	0.40
7	d	d	d	0.75
8	d	d	d	0.80
9				no crack
10				0.15
11			d	0.13
12	d	d	d	0.66
13	d	d	d	0.90
14	d	d	d	0.70
15	d	d	d	1.00
16			d	0.60
17			d	0.30
18	d	d	d	0.65
19	d	d	d	0.40
20				0.13
21			d	0.48
22				0.12
23-27, Material was removed and not available for inspection				
28		d	d	0.10
29		d	d	0.40
30			d	0.15
31			d	0.02
32				no crack
33	d	d	d	0.30
34	d	d	d	0.38
35	d	d	d	0.46
36				0.25
37				0.11
38		d	d	0.26
39			d	0.18
40	d	d	d	0.88
Total Detected (d)	13	17	28	32
False Calls	0	0	1	0

The maximum amplitude and phase angle of the impedance plane signals, taken from screen prints, were correlated with the maximum crack depth as measured on SEM micrographs. Despite scatter in the data points due to variations in the crack shape, type and location as well as the coil position with respect to the crack and the bolt hole, which affect the EC signals, a general trend appears to exist. As shown in Figure 5, for the material and inspection conditions used in this study, the trend is that the amplitude of the EC signal does not change significantly until the crack is about 0.5 mm deep, beyond that it increases with increasing crack depth. On the other hand, the phase angle of the EC signal shows an increasing trend with crack size until it reaches a maximum level and then starts to decrease. This decrease is attributed to the weakening of the induced field at larger depths which is governed by the operating frequency.

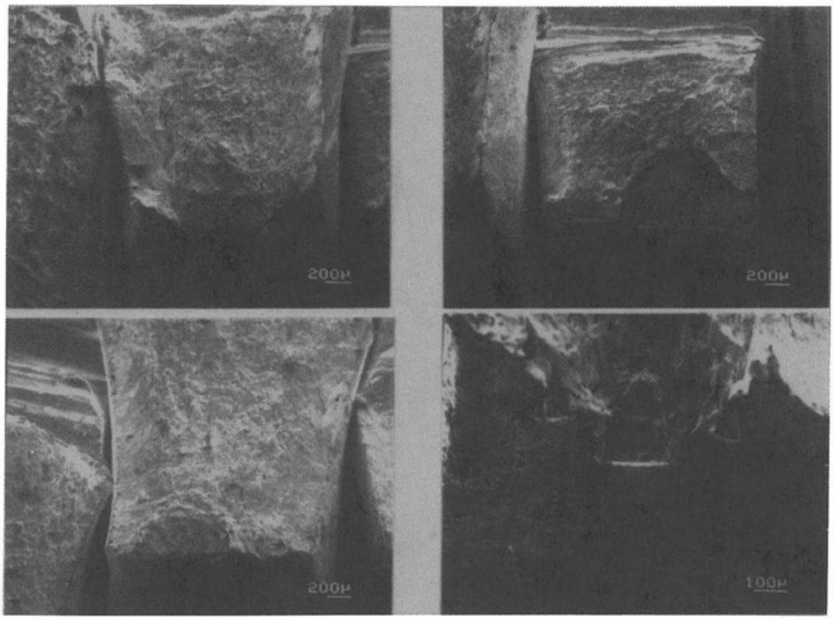

Figure 4. Examples of cracks seen in the bolt holes of compressor discs.

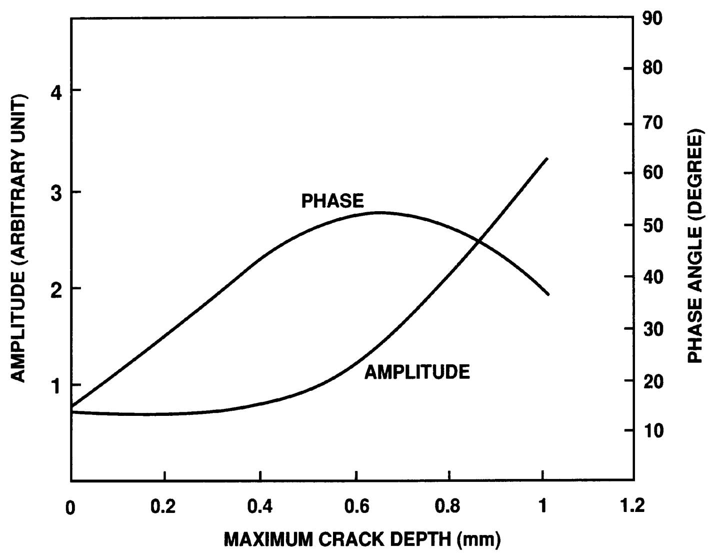

Figure 5. Correlations between the EC signal amplitude and phase angle with crack size.

The trends indicate that, if only the signal amplitude is used for crack detection, it is likely that some small cracks will remain undetected. By using both amplitude and phase angle of the eddy current signal, the chance of detecting small cracks increases. Further improvement in detectability can be achieved by using pattern recognition which takes advantage of multi-feature analysis and statistical classification to recognize very small cracks.

CONCLUSIONS

A standard eddy current instrument, an automated XYZ table and a commercial pattern recognition software package have been integrated into a system to inspect fastener bolt holes of aircraft engine components. The use of pattern recognition analysis provided significant improvement in the detection capability as well as the inspection speed. It was possible to indicate the presence of fatigue cracks in the bolt holes of a compressor disc in real-time.

The correlations between the EC signal amplitude and phase angle with the crack size indicate that both the amplitude and phase information are required to increase the detectability of small cracks. Further improvement in detection may be achieved by employing pattern recognition which take advantage of multi-parameter analysis and statistical classification to recognize very small cracks.

FURTHER WORK

A more extensive research project involving several service-retired components is currently in progress to determine improvements in the probability of detection of automated eddy current using pattern recognition analysis.

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